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WIND TUNNEL MODEL DESIGN AND TEST USING RAPID PROTOTYPE MATERIALS AND PROCESSES

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Abstract

Whether an airframe is a new design, modification of an existing design, or evaluation of a competing or foreign design, an accurate, high-confidence representation of the airframe aerodynamics is paramount to any low-risk design or evaluation effort. These aerodynamic estimates are used for vehicle and component sizing, performance estimates, and autopilot design and evaluation. The advent of new rapid prototyping manufacturing techniques and materials could provide a means to reduce the cost associated with the acquisition of a wind tunnel model (WTM), provided the data obtained with the rapid prototype model (RPM) were of sufficient fidelity to justify its use. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed a WTM design that consists of a steel strongback with rapid prototype plastic components attached to it to provide the overall vehicle configuration. In a test at the Lockheed Martin Missile and Fire Control–Dallas High-Speed Wind Tunnel (HSWT), this model (designated RPM-01) demonstrated acceptable data quality and test-to-test data repeatability with a geometrically similar steel and aluminum model. RPM-01 was built for approximately a quarter of the cost and a fraction of the time required of the all-metal high-fidelity model.

Program Objectives

The objectives of this research program were to demonstrate the feasibility of using a fused deposition modeling (FDM) process to create acrylonitrile/butadiene/styrene (ABS) plastic parts of suitable strength and fidelity to build a WTM in a fraction of the time and cost associated with a traditional all-metal WTM. The measures of success associated with this program were to

- Demonstrate the model's ability to survive the wind tunnel test environment.
- Deliver data quality that is within JHU/APL's previously achieved test-to-test repeatability levels.
- Reduce model fabrication costs by more than 50% of a traditional steel and aluminum model.

Program Accomplishments

RPM-01 was designed and fabricated at JHU/APL and tested in the Lockheed Martin Missile and Fire Control–Dallas HSWT from 20–22 August 2000. The model was built in less than half the time and for approximately one-third the cost of WTM-01. Fifty-three data runs were obtained during 14.91 hours of tunnel occupancy. Data were obtained for angles of attack (α) up to 20° and sideslip angles (β) to 10° for Mach 0.40 to 0.90. Various configurations and fin and canard materials were tested. A complete run log is provided in Figure 1.

The results of the testing demonstrated that the hybrid WTM (ABS fuselage with a steel strongback core) was not only more cost effective than a similar all-metal model, but provided acceptable data fidelity as well. Extensive post-test analyses determined the cause for failure of some components and identified candidate epoxies with stronger material properties and temperature resilience.

Model Description

In 1997, JHU/APL built a high-fidelity 25% scale steel and aluminum model of a canard wing airframe with an underbody flow through inlet and integral top-mounted launch lugs. This model, designated WTM-01, would provide the cost, schedule, and data quality benchmarks for RPM-01, which was fabricated for this research effort. The WTM-01 model canards and tails are arranged in the + and x orientation, respectively, when the vehicle is at 0° roll attitude. The horizontal canards are fixed at 5° leading edge up while the vertical canards are deflectable to provide yaw control. The four tails incorporate trailing edge elevons that deflect to provide airframe pitch and roll control. An inlet fairing for the model was designed to prevent flow through the inlet and present a clean aerodynamic surface to the oncoming flow.

Mach No.	R_N/ft	Configuration	$\phi = 0°$	$\phi = 90°$	$\alpha = 0°$	$\alpha = 5°$	$\alpha = 10°$	$\alpha = 20°$	$\beta = 0°$	$\beta = 5°$	$\beta = 10°$
0.40	3.1M	1	11 (B)	12 (B)	13 (A)		14 (A)	15 (A)			
		2	31 (B)	32 (B)							
		3	51 (B)	52 (B)							
		4			71 (C)	66 (C)	65 (C)	64 (C)	61, 181 (B)	62 (B)	63 (B)
		5							101 (B)		102 (B)
		6							121 (B)		122 (B)
		7							141 (B)		142 (B)
0.75	5.2M	4			82 (C)	86 (C)	85 (C)		81 (B)	83 (B)	84 (B)
0.90	5.4M	1	21 (B)	22 (B)	23 (A)		24 (A)	25 (A)			
		2	41 (B)	42 (B)							
		4			92 (C)		96 (C)	95 (C)	91, 171 (B)	93 (B)	94 (B)
		5							111 (B)		112 (B)
		6							131 (B)		132 (B)
		7							151 (B)		152 (B)

Configuration Codes:

1. Body alone
2. Body + canards (vertical canards: metal, horizontal canards: infused plastic)
3. Body + canards (vertical canards: metal, horizontal canards: cast resin)
4. Full configuration = body + 4 metal canards + 4 metal fins + inlet + lugs
5. Full configuration = body + 4 metal canards + 2 metal fins (1 and 4) + 2 rapid prototype fins (2 and 3) + inlet + lugs
6. Full configuration = body + 4 metal canards + 2 metal fins (1 and 4) + 2 infused plastic fins (2 and 3) + inlet + lugs
7. Full configuration = body + 4 metal canards + 4 cast resin fins + inlet + lugs

Sweep Codes:

Roll: A = $0° \leq \phi \leq 270°$

Pitch: B = $0° \leq \phi \leq 20°$

Yaw: C = $0° \leq \beta \leq 10°$

Figure 1 HSWT 1307 Run Log

The model was tested primarily with the fairing in place; however, data with the inlet flowing were obtained to assess the aerodynamic impact because of the flowing inlet. WTM-01 was tested in the Veridian Calspan 8x8-ft transonic wind tunnel in Buffalo, NY, at the following test conditions:

- Mach: $0.40 \leq M \leq 0.90$
- Angles of attack: $-5° \leq \alpha \leq 20°$
- Angles of sideslip: $-10° \leq \beta \leq 10°$

A more detailed model description and post-test report are provided in References 1 and 2.

RPM-01 is a 15% scale model of the above airframe, consisting of a steel strongback or backbone with ABS plastic parts attached to it to create the outer moldline of the model. The aerodynamic surfaces (canards and fins) for the model pass through the ABS plastic skin and attach directly to the strongback with screws. A schematic diagram of the RPM-01 buildup is provided in Figure 2, and a detailed description of the model design and construction is provided in Appendix A.

This design approach was chosen to address deficiencies identified in earlier research performed by Marshall Space Flight Center (MSFC) (References 3 through 5). Their research focused on the various rapid prototype methods and materials available and which of these provided the best performance with regard to model construction and data quality. Their research concluded that "rapid prototype methods and materials can be used in subsonic, transonic, and supersonic testing for initial baseline aerodynamic database development" and "the accuracy of the data is lower than that of a metal model due to surface finish and tolerances." Their research indicated that the models made using the FDM-ABS and stereolithography (.stl) materials and processes provided the best results. However, the FDM-ABS model data did diverge from the metal model results at high loading conditions, thus producing unsatisfactory results. These differences were attributed to surface finish, structural deflection, and tolerance deviations when the material was grown.

The JHU/APL model was fabricated using the FDM-ABS material and rapid prototype manufacturing process. The steel strongback used in the model provides rigidity to the complete model and allows the

aerodynamic surfaces to be mounted directly to it. This reduces or eliminates any structural deflection the model body and metal fins might experience in the test. The ABS plastic and cast resin fins did experience flexure and sometimes failure under load during the test.

Another advantage provided by the strongback design is the ability to make larger models and reduce the uncertainties because of manufacturing tolerances and model scale. RPM-01 was a 15% scale model with an overall length of 25.465 inches. A sketch of the model and pertinent dimensions is provided in Figure 3. The machine used to manufacture the plastic components has a 9-inch maximum limit on component length and a quoted manufacturing tolerance of ±0.005 inch. For RPM-01, this tolerance scales to ±0.030 inch on the full-scale vehicle, which is comparable to a full-scale manufacturing specification. If RPM-01 had been limited to the maximum 9-inch length as were the MSFC models, the same ±0.005-inch manufacturing tolerance becomes ±0.094 inch full scale, well in excess of the full-scale specification.

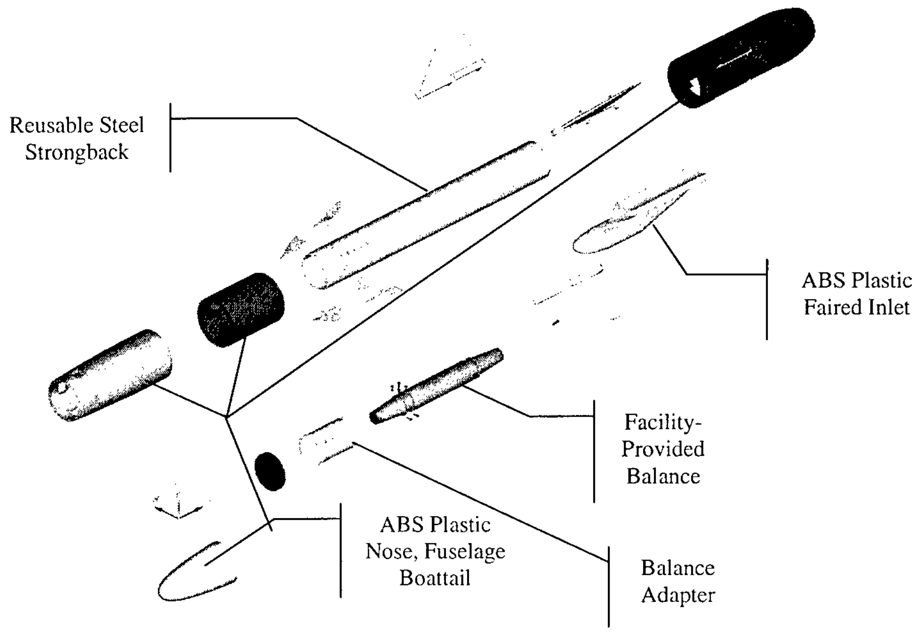

Figure 2 Model Exploded View

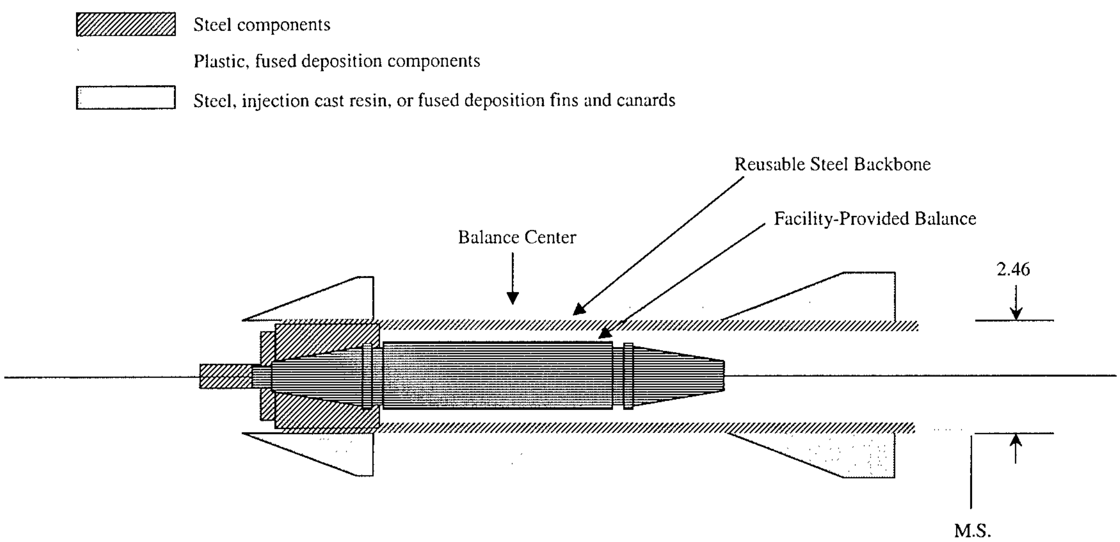

Figure 3 Model Schematic

RPM-01 obtains its size by employing three cylindrical interlocking components that fit tightly over the strongback to form the fuselage/boattail assembly. The model nose attaches separately to the strongback via a threaded spindle assembly. The model inlet, fins and canards passed through the plastic fuselage skin to mount directly to the strongback for strength. The model launch lugs attach to the plastic skin with screw and helicoil attachments. To test a clean symmetric cone-cylinder configuration, rapid prototype filler blocks for the canard, fin, and inlet access holes were manufactured. This allowed the model's symmetry characteristics to be quantified as a function of roll angle.

Aerodynamic Surfaces

Four sets of missile control surfaces (i.e., canards and tails) were fabricated for testing: steel, ABS plastic, ABS plastic with vacuum epoxy infiltration (vacuum-infused ABS), and cast mold C1511 urethane resin. The use of the steel tails and canards provided a rigid reference for comparison against the nonmetallic tails to discern elastic and nonlinear behavior as a function of aerodynamic loading in subsonic and transonic Mach number regimes at various model roll and pitch orientations.

The ABS plastic surfaces were created (grown) on the FDM machine whereby model parts are built up in thin slices or roads (i.e., 0.010 inch) of ABS plastic with alternating pattern directions. Even though the parts were manufactured using the maximum density possible, the resultant components are still porous. As an inexpensive method to fill the microscopic pores and increase stiffness, the ABS components were immersed in an epoxy bath while under vacuum pressure. This process, deemed "vacuum infusion," results in a more solid component because air in the porous areas has been displaced by the epoxy.

The third nonmetallic surfaces tested were cast resin molded surfaces. These were manufactured by creating a mold of a specially prepared ABS part that was grown on the FDM machine. The surfaces of the part are filled, sanded, and primed to provide the smoothest possible surface finish and then treated with a silicon release agent. This finished part is then used as a master to create a silicon mold. Vent holes are placed in the mold, and the desired epoxy resin is injected into the mold cavity using a hypodermic needle. The aerodynamic test results obtained with these components are discussed later in this paper.

Test Facility

The Lockheed Martin Missile and Fire Control–Dallas HSWT is an intermittent blow-down-to-atmosphere tunnel with a Mach number capability of 0.30 to 4.80 and dynamic pressure range from 300 to 5000 psf. The tunnel is operated by the controlled discharge of compressed air supplied by eight storage tanks that are charged by three series-connected, multistage, centrifugal compressors driven by an 8000-hp electric motor. Air storage volume is 40,000 ft^3 with a maximum storage pressure of 500 psi at 100°F.

The tunnel uses both supersonic and transonic test sections, depending on the desired test conditions. Each test section is 4x4 ft in cross-section and approximately 5 ft long. For operation at Mach >1.50, the supersonic test section is employed. A single-peak variable diffuser is located downstream of the test section and allows operation at lower stagnation pressures than would be possible with a fixed diffuser. For subsonic and transonic operation ($0.30 \leq M \leq 1.50$), the variable diffuser is removed and replaced with the perforated wall transonic test section having 22% porosity. The transonic plenum is pumped by ejector action of the main tunnel airstreams acting on controllable ejector flaps located downstream of the test region. Adjustable choking flaps, also located downstream of the test region, are used to control Mach number.

The HSWT sting cart is a servo-controlled hydraulically actuated cart capable of a -13° to +23° sweep range while maintaining the center of rotation on the tunnel centerline. Fixed offset adapters can be installed to extend the available pitch range. Sweep rates up to 5° per second are available. A remotely controlled roll sting can be added to provide multiple pitch, roll, and yaw sweep capability.

Test Results

As shown in Figure 1, the RPM-01 test was conducted in three phases. Phase 1 consisted of the RPM-01 body alone. This was necessary to assess any model or tunnel asymmetries that may be present in the data and to provide a baseline for the alternate nonmetallic canard studies to be done in phase 2. Both roll sweep data at fixed pitch angles and pitch sweep data at fixed roll angles were obtained. Phase 1 test results (Figure 4) indicate that good data symmetry was obtained between the quadrants. Because four interlocking cylindrical components were required to build up the fuselage, any tolerance problems or mismatches created when the parts were grown would have been apparent in this data. Therefore, the ABS plastic cylinders built up over the steel backbone possess sufficient fidelity (and

roundness) to allow acceptable roll sweep data to be obtained. The ability to obtain roll sweep data is important in missile testing because it provides an efficient means of gathering data for both trim and non-trim orientations.

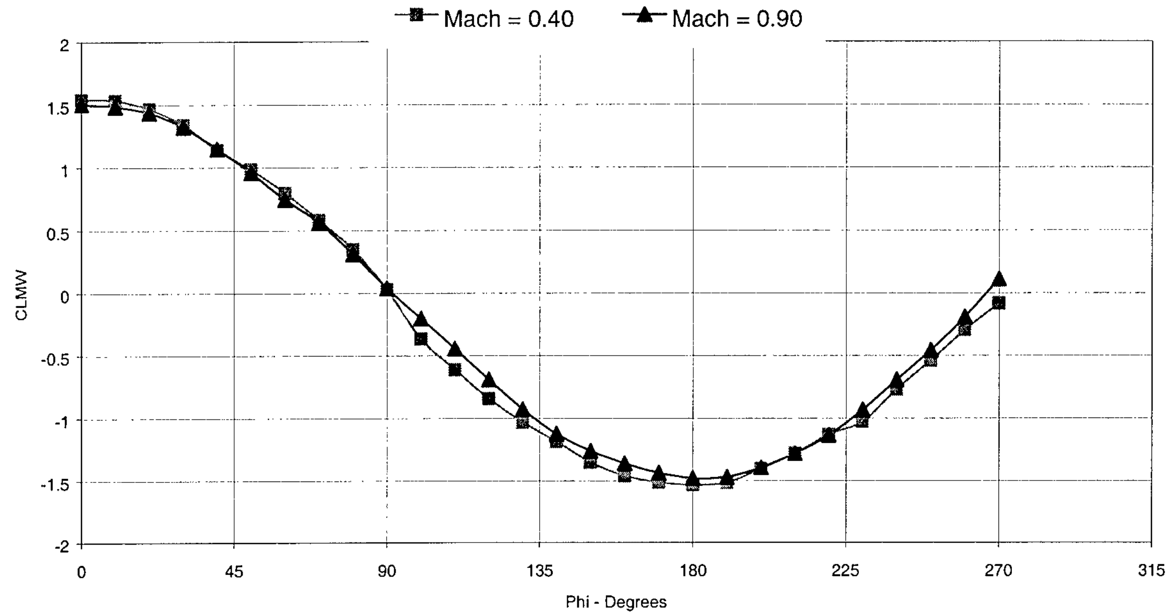

Figure 4 Phase 1 (Body Alone) Test Results

The alternate canard material studies conducted during phase 2 were done on the body/canard configuration. For these runs, undeflected steel canards were installed horizontally, and the alternate material canards (ABS plastic, vacuum-infused ABS plastic, or resin cast) were installed vertically. Pitch sweep data were obtained at 0° and 90° of roll. Increments between the phase 1 and phase 2 runs were taken to assess the fidelity of the data acquired with the nonmetal canards.

The results of the body-canard testing are provided in Figure 5. It can be seen that at Mach 0.40, the vacuum-infused ABS canard results are comparable to those obtained with the steel canards. The resin cast canards were unable to withstand the air temperature during the run and became extremely pliable under load, resulting in unacceptable performance at Mach 0.40. They were not tested again at Mach 0.90. An indication of the achieved in-test repeatability at Mach 0.40 is also provided in Figure 5. At Mach 0.90, the vacuum-infused canards provided acceptable results up to 10° angle of attack. At that point, one canard failed completely, resulting in the reduced normal force coefficient shown in Figure 5 and a subsequent rolling moment coefficient not shown.

To save money during the RPM-01 model design and fabrication, the same design was used for both the metal and non-metal canards. The design used a spindle that attached to a base that allowed the canards to deflect. The spindle was the point of failure for the vacuum-fused ABS canards. A better approach would have been to use a unique design for the ABS canards that would maximize the cross-section at the intersection with the component base.

Finally, the failure of the cast resin canards was very disappointing and unexpected because temperature was a factor considered when the casting resin was chosen. It was determined that for an airfoil application such as this, the thin wafer resin properties need to be evaluated rather than the more conventional cylindrical properties. Several alternate resins were evaluated following the wind tunnel test to assess their temperature and strength properties. These results are discussed further in Post-Test Failure Analysis and Testing.

Phase 3 was the full-up configuration comparison to the high-fidelity WTM-01 data. Pitch sweep runs at 0° and 10° sideslip and yaw sweep runs at 0°, 10°, and 20° angle of attack were done. Steel canards were used for all the comparisons, but steel and alternate material fins were tested. Figures 6 through 8 show that good test-to-test and facility-to-facility repeatability was obtained between WTM-01 and RPM-01 with steel fins. Figure 9 includes facility-to-facility uncertainties overlaid on the data. These uncertainties were derived from historical Standard Missile test results using high-fidelity steel models in different facilities. These results quanti-

tatively demonstrate that the RPM with steel fins and canards provides acceptable test results when compared with a high-fidelity steel model in another facility.

Finally, the feasibility of using nonmetal fins was investigated during phase 3. Fins were made using the same materials and processes described previously for the canards. Complete sets of resin fins were made, as were pairs of ABS plastic and vacuum-infused ABS plastic fins. Once again the resin fins became soft and pliable during testing, but because the fins were much thicker than the canards, the resulting bending was less but still unacceptable. The ABS fins tested were installed in the upper and lower right fin locations with steel fins installed on the left side of the model. Both sets of ABS plastic fins survived testing at Mach 0.40 and 0.75 and 0° sideslip testing at Mach 0.90.

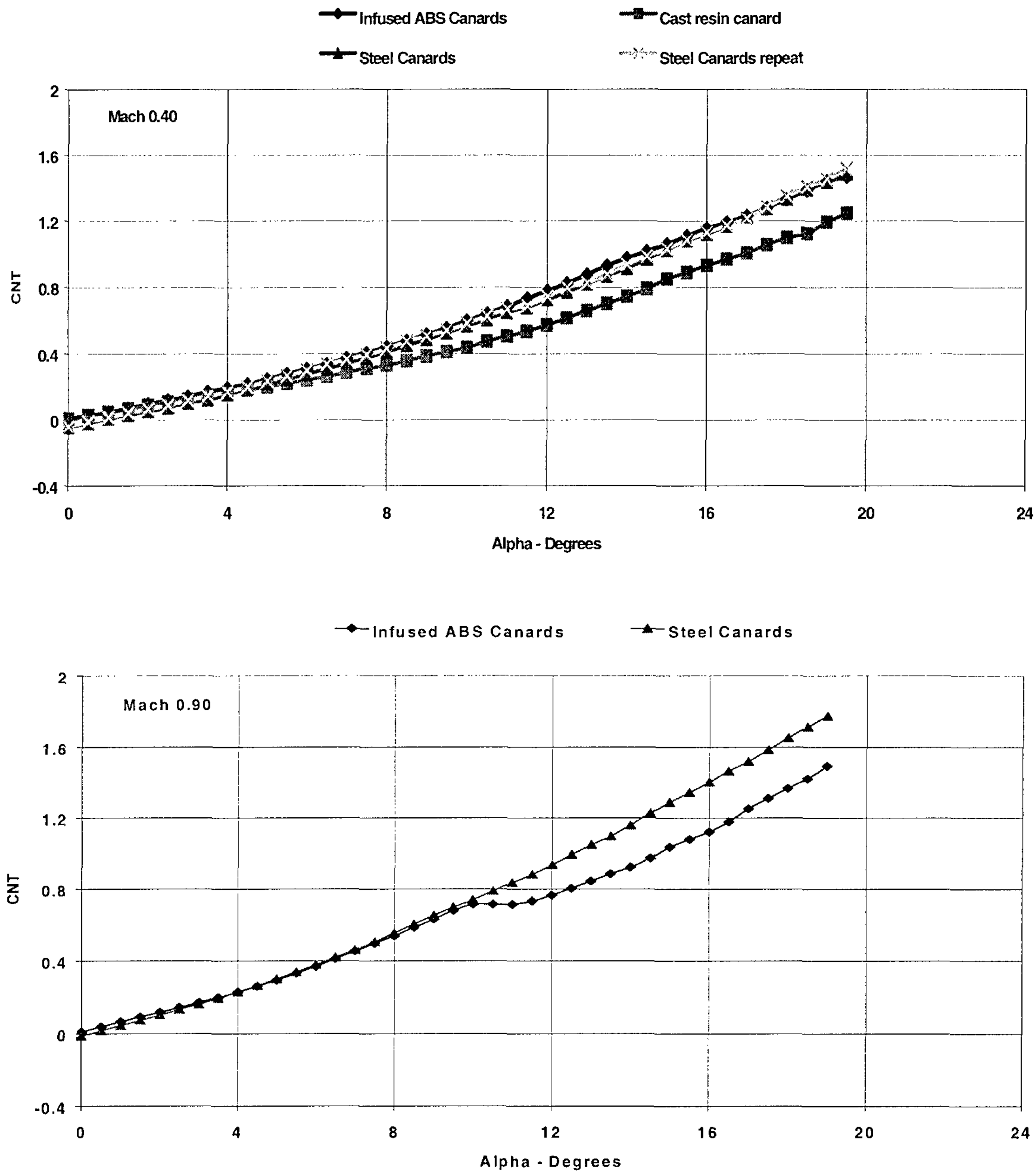

Figure 5 Phase 2 (Body/Canard) Test Results

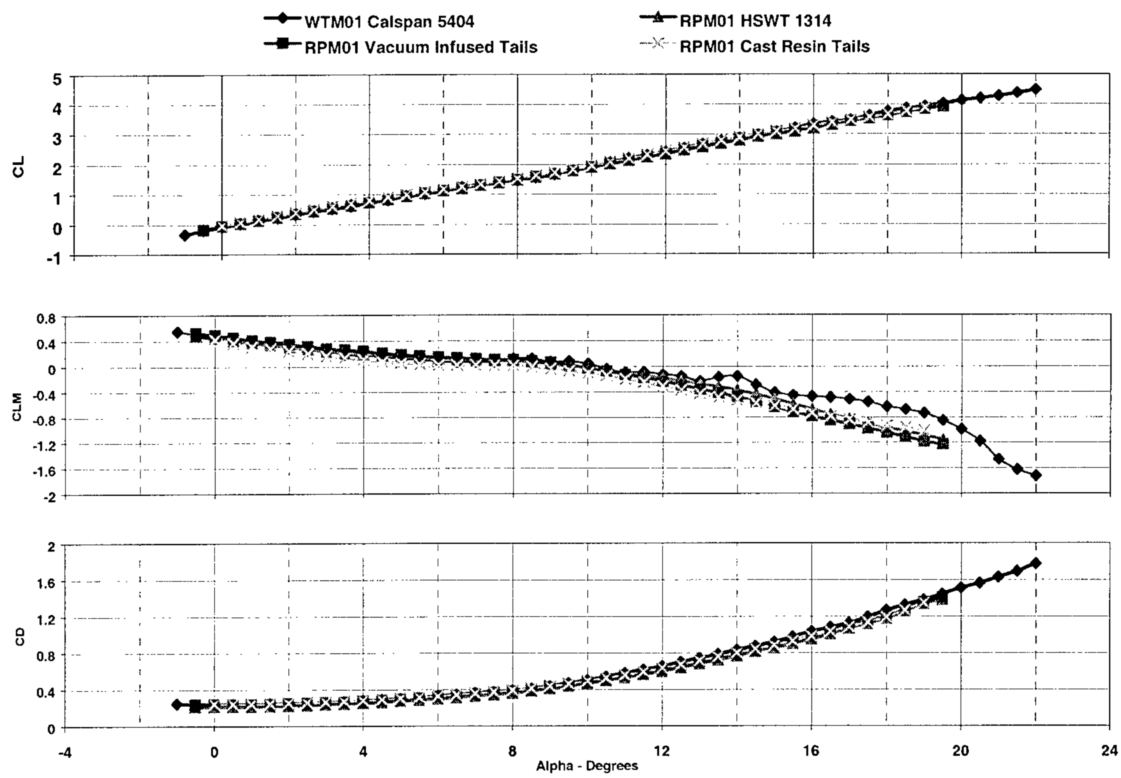

Figure 6 Test-to-Test Comparison, Mach 0.40

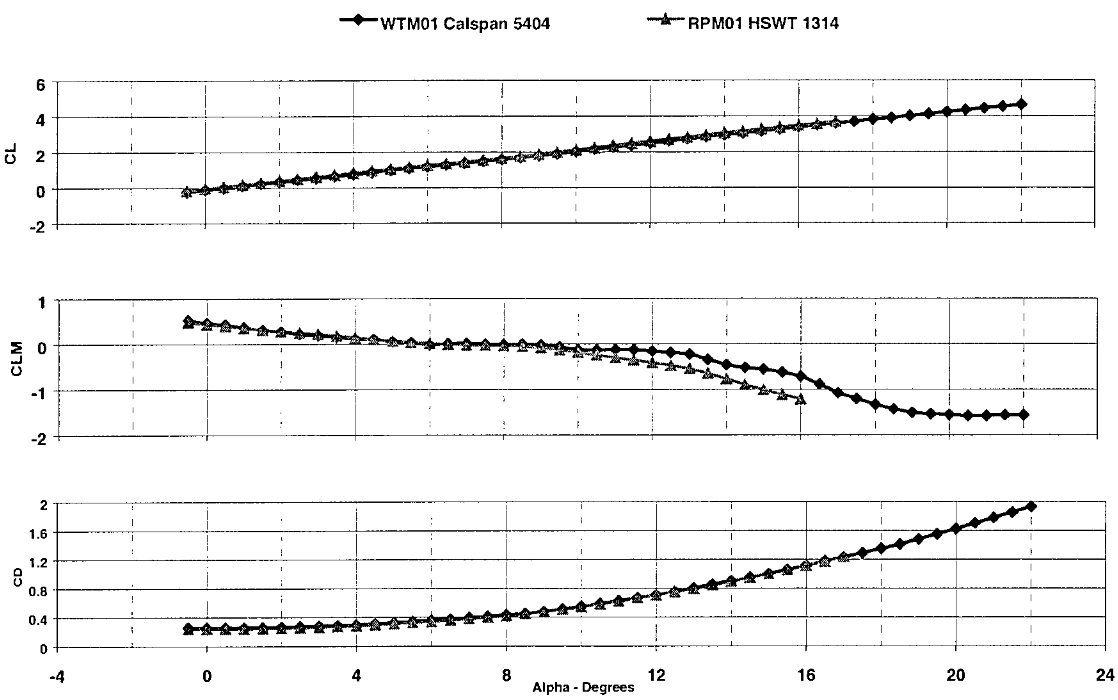

Figure 7 Test-to-Test Comparison, Mach = 0.75

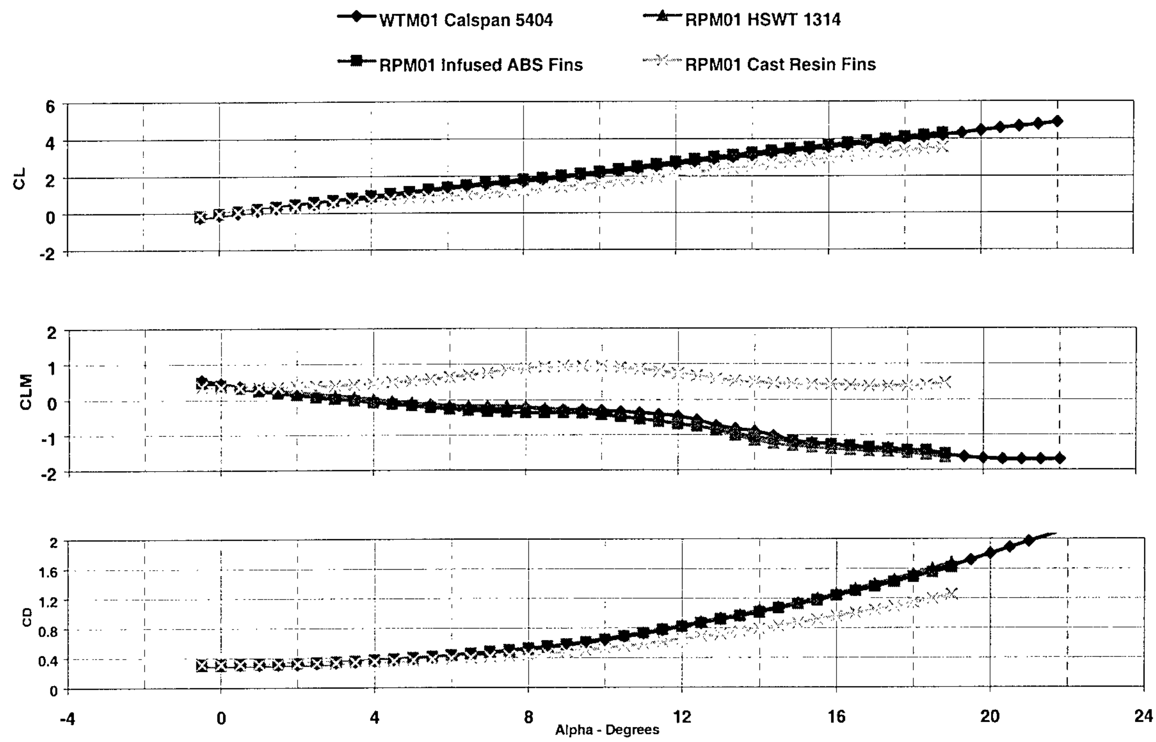

Figure 8 Test-to-Test Comparison, Mach = 0.90

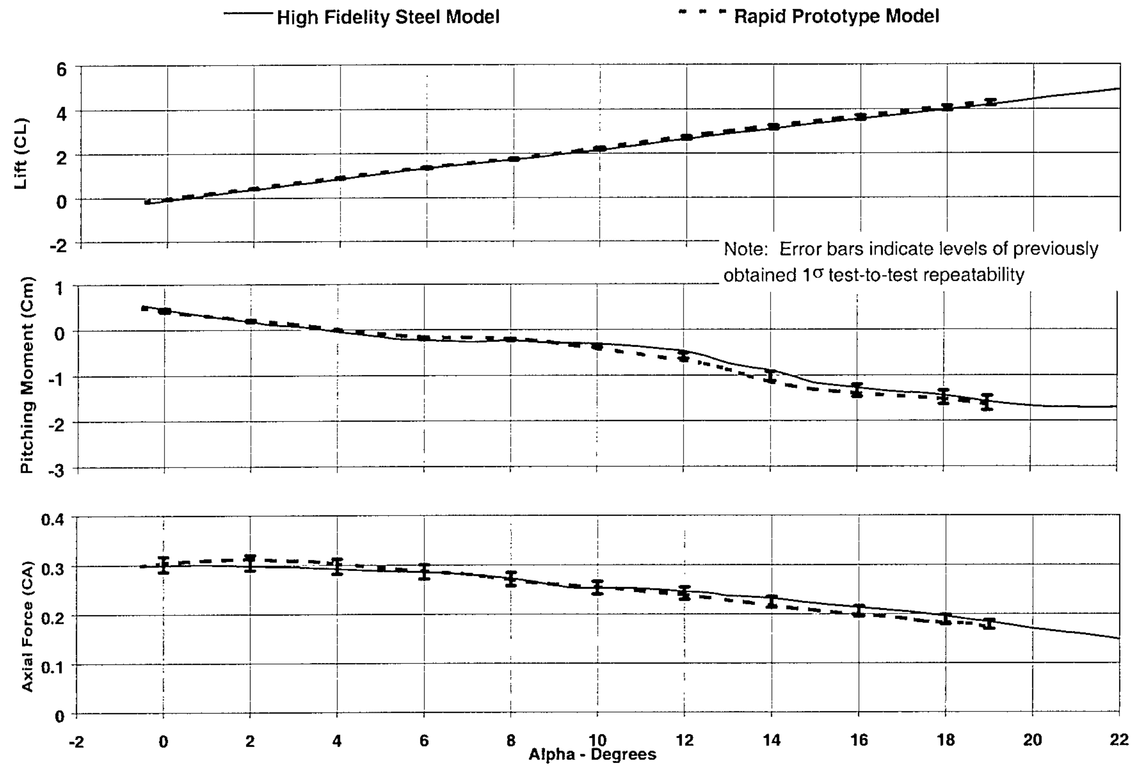

Figure 9 Test-to-Test Comparison, Mach = 0.90 with Uncertainty Overlay

During a blow, pitch sweep data up to 20° angle of attack were obtained at 0° sideslip. The model was then snap rolled air-on at 20° angle of attack to obtain the 10° sideslip orientation, and data were acquired as the model was pitched back down to 0° angle of attack. The ABS fins failed during the model roll to 10° sideslip at $\alpha = 20°$. The aerodynamic loading and dynamics due to the snap roll combined to fracture the ABS fins at the mounting pad where the aerodynamic surface intersected the base. The fin load at this condition was estimated using computational fluid dynamics to be 55 pounds normal force. Static testing of the component confirmed the failure under aerodynamic loading. Additional results of the post-test failure analysis are discussed later.

A comparison of the data obtained using the nonmetal fins is provided in Figures 6 and 8. It can be seen that at low Mach numbers, the ABS plastic fins provide good-quality data. However, as the speed and angle of attack increase and fin loads increase, data fidelity suffers because of fin flexure. Based on these results, the authors conclude that the ABS plastic fins are not suitable for high-speed testing, but further research into cast resin materials is necessary to identify a resin or compound that can withstand the test environment.

Post-Test Failure Analysis and Testing

Following the test, several new RPM-01 resin tails were cast and statically tested to identify better materials for use in future testing. Because the mold had already been made, creation of new fins was relatively simple and inexpensive. The resins for these fins included Smooth-On C1511 (rigid urethane casting compound), Dexter® EL355, Dexter® Hysol 9396, and Hysol 9396 +18% end-milled fiberglass fill. In addition to the new cast fins, a new vacuum-infused ABS tail was made using higher strength epoxy as the filler infused into a more porous ABS tail (Resin Fusion 8601/8602 infiltrated to 0.050-inch honeycomb structure).

A thin wafer test sample of each new tail material also was created at the same time to evaluate the temperature sensitivity of the tails as part of a dynamic material analysis; test results are provided in Figure 10. As shown in the figure, the C1511 resin is sensitive to temperature and suffers an order of magnitude strength loss between 50°C and 75°C (122°F to 167°F). The tunnel air was approximately 130°F during testing and explains the observed failure during air-on testing. The Hysol 9396 epoxy would have been a much better choice for testing at this facility.

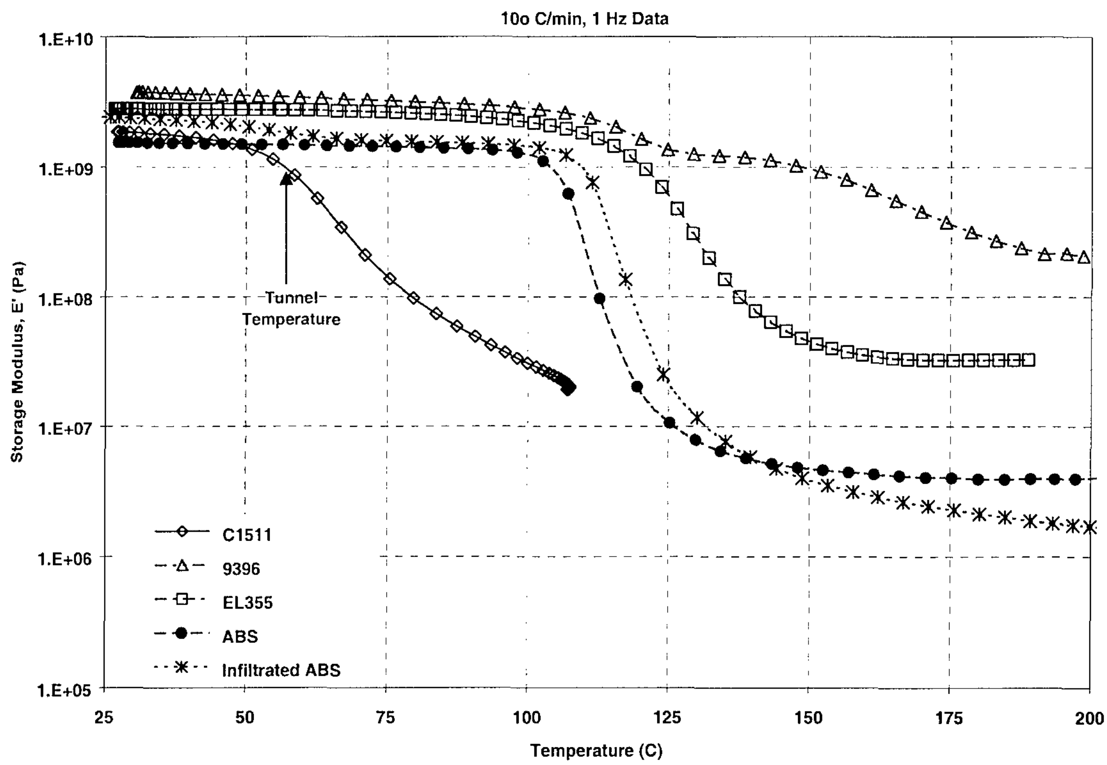

Figure 10 Material Sensitivity to Temperature

The failure of the ABS tail during testing was not unexpected. The failure of the vacuum-infused tails and the way they failed raised some questions. Following the test, an X-ray analysis of the vacuum-infused tails revealed the vacuum infusion did not permeate the tail as expected. This result (Figure 11) indicates that only about 65% of the tail was reinforced with epoxy and led to development of the 0.05-inch honeycomb structure for static testing.

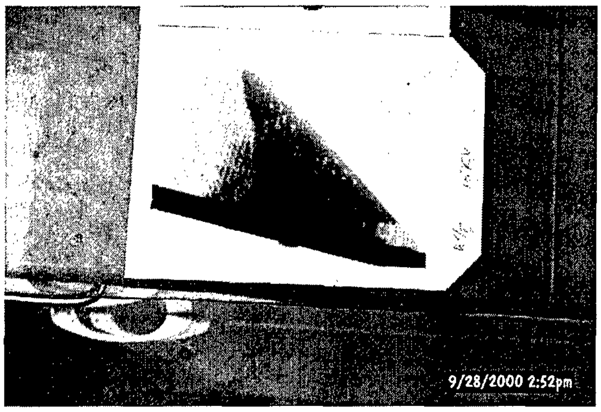

Figure 11 Vacuum Infusion X-Ray Infiltration Results

Finally, all tail samples were tested to failure in a load cell mounted in the same manner as the tails mounted to the RPM-01 strongback (Figure 12). The static load cell testing validated that the Hysol 9396 epoxy resin has superior stiffness properties based on the increased slope of the curve presented in Figure 13. The Hysol and EL355 tail surface did not fracture at the root as with the ABS, but actually fractured at the base around the hole pattern where screws were used to mount the tail to the mounting bracket. Only the ABS and C1511 nonmetallic materials were wind tunnel tested. All of the static load ABS tail structures fractured at the root chord near the base similar to what happened during the wind tunnel test. These results are provided in Figure 13.

Figure 12 Static Load Test of RPM-01 Tail

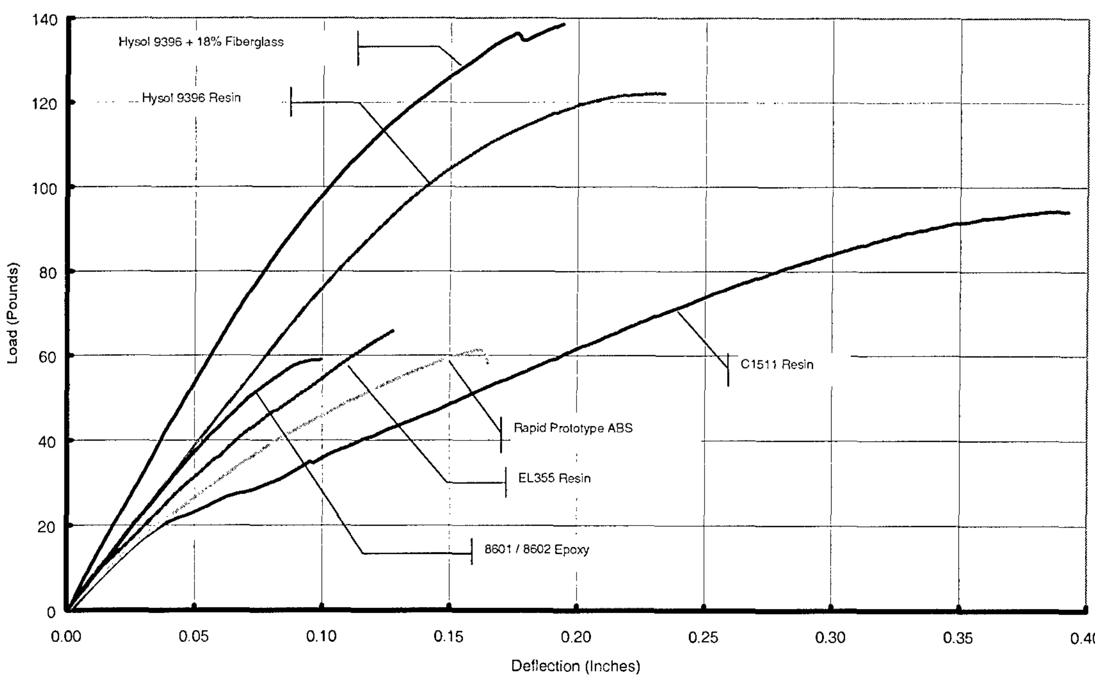

Figure 13 Static Load Test Cell Results

Conclusion

The results of this project demonstrated that the use of rapid prototype manufacturing technology and materials can significantly reduce the time and cost associated with the fabrication of a scale model suitable for wind tunnel testing. It was further demonstrated that by using an innovative hybrid design consisting of ABS plastic parts built on to or attached to a reusable steel strongback, the data obtained with such a model are comparable in quality to data obtained on an all-metal high-fidelity model. These capabilities were demonstrated in the transonic regime (up to Mach 0.90) using metal fins and canards. Post wind tunnel test research and analysis of the nonmetal aerodynamic surfaces verified the in-test failures of these surfaces and identified the materials and manufacturing processes better suited to withstand the wind tunnel test environment.

The authors conclude that these new surfaces not only could survive supersonic test conditions, but would have sufficient strength to deliver accurate data under these conditions as well. A wind tunnel test, to be conducted in 2001, will hopefully demonstrate the ability of these nonmetallic surfaces at supersonic conditions.

The combination of these manufacturing technologies and materials should make wind tunnel testing a viable and affordable option to programs developing a new configuration or evaluating a previously untested configuration. The availability of wind tunnel data early in the design process would greatly reduce the risk associated with a configuration down select and could preclude surprises discovered later in the full-scale development phase of a program.

Appendix A – Fabrication Details of RPM-01

RPM-01 was manufactured using FDM-ABS plastic panels attached to a cylindrical steel strongback. The strongback provides strength and rigidity to the plastic model and allows larger scale models to be built as well. The strongback, fabricated from 304 stainless steel, is a 17.625-inch long cylinder with a 2.25-inch outer diameter and a 1.874-inch inner diameter. The surface of the cylinder has a surface finish of 32.

The balance adapter was fabricated by the Lockheed Martin Missile and Fire Control–Dallas HSWT, which also performed the final honing of the strongback inside diameter to achieve a zero tolerance fit between the balance adapter and the strongback. (Note: The inner surface of the strongback was only machined from one end to accommodate the balance adapter.) The remainder of the strongback is unfinished. Threaded screw holes for attachment of the canards, tails, and faired inlet were located in the strongback to meet model design requirements. Finally, the inside forward end of the strongback was machined to a 2.125 inch diameter and threaded to accommodate the spindle for attachment of the model nose. The spindle is also fabricated of 304 stainless steel and has a 2.125-inch diameter threaded base for mating to the strongback and a 0.5-inch diameter threaded spindle for attachment of the ABS plastic nose.

The ABS plastic nose, fuselage components, boattail, faired inlet, fins, canards, launch lugs, and assorted filler blocks were all manufactured using a Stratasys Inc. FDM-1650 machine. The parts were designed and solid geometry models were created using Pro-E design software and output as an .stl file. (This is an output option built into Pro-E.) The geometry information contained within the .stl file was then mathematically broken down into horizontal slices and transferred to the FDM machine for fabrication.

The FDM-1650 operates at high temperature to melt the ABS plastic (or wax). These materials are fed into a temperature-controlled extrusion head, where they are heated to a semi-liquid state. The melted plastic comes out in an extruded string of hot liquid and paints an ultra-thin layer of plastic 0.010 inch thick onto a fixtureless base. The layers are built one on the other. The material solidifies, laminating the preceding layer. Because the plastic is hot and therefore very pliable, a supporting system is built underneath to support the prototype pieces.

Because of FDM-1650 size constraints, the fuselage was built up as three sections plus the nose. The inner diameter of the components was chosen to be equal to the outer diameter of the strongback. Because of shrinkage during fabrication, the inside of the components were lightly sanded to achieve a near-zero tolerance fit over the strongback. The outer surfaces of the components were sanded to smooth the surface and remove the burrs that accumulate as the part is grown and then sprayed with an aerosol solvent (Sandfree) and wiped clean to produce a smooth clean surface. There are no attachments between the ABS fuselage components and the strongback.

Each fuselage component has an interlocking tab to locate and attach it to the next component. Longitudinal and rotational position is maintained on the strongback via attachment of the fins, canards, faired inlet, or filler blocks for these components. The slots and holes required in the individual fuselage components that allow the fins, canards, and inlet to attach directly to the strongback are incorporated into the design during the Pro-E geometry development and included in the .stl file description. As such, these geometry details are

created as the part is grown on the FDM-1650. The screw holes to attach the launch lugs were drilled into the center and aft fuselage sections after fabrication on the FDM machine. Helicoils were inserted into the drilled holes to provide the threaded surface.

The nose is created the same as the fuselage components with the exception that a hole is designed into the base section of the nose. After fabrication, a locking helicoil is inserted into the hole to provide the threaded surface for attaching to the spindle.

The ABS launch lugs, faired inlet, canards, and fins were all fabricated in the same manner as the fuselage components. The tails and canards were small enough to allow them to be fabricated four at a time in the FDM machine. In addition to the rapid prototype ABS fins and canards, additional fins and canards were fabricated using the following two processes:

- A JHU/APL-developed patent-pending process to infuse epoxy into the ABS components
- Casting the components out of resin using a soft mold created from a specially prepared ABS component

The epoxy-infused components are created normally on the FDM machine and surface sanded. They are then immersed in an epoxy bath and subjected to a vacuum to remove the air contained within the rapid prototype parts and replace it with the resin epoxy. The parts are then removed from the container, excess resin is wiped from the outer surface of the part, and the resin-impregnated part is allowed to cure. This results in a FDM rapid prototype plastic part that is no longer porous and has significantly greater mechanical properties than that of the original part. The final cured part is then sanded and wiped with the Sandfree aerosol solvent to provide the relatively smooth surface used in the wind tunnel test.

Finally, the third set of fins and canards investigated, which showed the most promise for further evaluation, were the cast resin components. These fins and canards were fabricated by first growing a master fin and canard in the FDM machine. These components were then sanded and treated with body filler to fill in surface pores and cracks. Next, a sandable primer paint was applied to coat the surface. The tail was then staged into clay to a break-away plane with care to remove any excess clay from surfaces and edges. A release agent was sprayed on the tail and clay surfaces. A metal frame was constructed around the clay to contain the pouring of silicon resin.

Once cured, the silicon mold was turned over and the other half was prepared with release agent and poured with silicon to mold the other half of the tail along the break-away plane. The removal of the rapid prototype tail left an internal cavity of the tail. With the use of some vent holes, a hypodermic needle was used to pressure fill the cavity with several types of epoxy resins. If high-pressure injection plastic casting is required, a hard tool mold can be made from the staged clay process by substituting a metal epoxy surface coat for the silicon. Thermalset plastics like polycarbonates can be used to make parts for higher strength and durability if required.

Finally, after all components were fabricated, the assembly of the model on the strongback proceeded as follows:

- The forward fuselage section was slid onto the strongback from the aft end of the strongback until only the interlocking tab remained.
- The center fuselage section was mated to the forward section via the interlocking tab and the combined sections slid forward until only the center fuselage tab remains off the strongback.
- The aft fuselage/boattail section was attached via the interlocking tab and the three combined sections translated forward to align the necessary holes in the strongback to the matching slots and holes in the plastic skins.
- The nose of the model was attached to the strongback by screwing the metal spindle into the forward end of the strongback and then screwing the threaded ABS nose onto the spindle.

At this point the entire fuselage has been completely assembled and the remaining components added as needed. For RPM-01, several configuration options were available, with all the optional components attached using screws and common screw holes. If the body-alone configuration were to be tested, the filler blocks would be installed in lieu of the canards, inlet, and fins. If the full-up configuration was desired, the canards are installed using four screws per canard. These screws pass through the canard mounting pad and screw directly into the strongback. The fins and inlet attach in the same way. Because the launch lugs are not subjected to large aerodynamic forces, it was satisfactory to screw them into the ABS fuselage using helicoil attachments.

Appendix B – List of References

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